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Characterization of Dynamic Soil-Pile Interaction by Random Vibration Methods: Experimental Design and Preliminary Results

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Abstract: Preliminary results are presented for full-scale vibration tests of piles using random vibration methods and a new servo-hydraulic inertial shaker testing system. Separate tests of vertical and coupled horizontal-rocking modes as well as hybrid multi-mode tests were performed on two steel HP 10x42 piles installed to a depth of 20 ft at a site containing soft clays. One pile was tested in the natural soil profile while the other had a cement deep soil mixed (CDSM) improved zone near the surface. Three excitation techniques were examined using a range of forcing intensities to determine the optimal testing configuration. The multi-modal vertical-eccentric test format was investigated as an efficient alternative to traditionally separate tests having vertical or horizontal forcing. Design of the experimental testing system is described, followed by a preliminary comparison of results from the various test configurations. Measurements indicate that the new excitation and instrumentation systems were successful in stimulating and capturing the broadband dynamic response of the soil-pile system for use in validating and calibrating advanced 3D computational continuum models.

1. Project Goals: The primary goal of this NEES Payload project is to improve experimental and computational tools to help bridge the gap between theory and observation for fundamental problems of dynamic soil-pile interaction. The study employs techniques of random vibration theory for efficient experimental and analytical characterization of the dynamic behavior of piles and soils. An inverse-type optimization approach is used, wherein the motion of the pile cap and soil surface are calculated using computational continuum models for the pile and soil domains, with beam-column theory for the un-embedded portion of the pile and rigid body dynamics for the pile cap. The soil properties are then varied in the model and optimized through a signal matching procedure via minimization of the misfit between the calculated and observed responses. In the computational modeling phase of the study, pile and soil domains are treated using a rigorous three-dimensional

boundary element program featuring a regularized multi-domain formulation [1], a library of layered viscoelastic half-space fundamental solutions to handle vertical heterogeneity of the far-field [2], families of singular and adaptive gradient (AG) elements [3] for treating stress singularities and discontinuities, boundary element-compatible structural beam-column elements for the pile domain, and an adaptive integration algorithm to ensure accuracy of the coefficient matrices. Similar to common non-destructive geophysical techniques, the approach developed in this study uses small-strain wave propagation to infer information about the soil properties, but also inherently includes the effects of pile installation and actual pile-soil contact conditions. In this paper, the design of the experimental setup will be presented, along with preliminary experimental results and their interpretation.

The present payload project uses a soil site and reaction piles from the NEESR-SG project entitled "Understanding and Improving the Seismic Behavior of Pile Foundations in Soft Clays" (Grant #0830328), which involves dynamic and cyclic lateral tests of open-ended pipe piles in soft clays similar to soils commonly found in seismically active areas. Current seismic design codes impose limits on lateral displacements of pile foundations in order to mitigate the development of plastic hinges below grade. Weak or liquefiable soils, however, may not be able to provide the required magnitudes of lateral resistance, in which case admixtures may be used to improve the soil's mechanical properties. The dynamic behavior of piles in such improved soft soils is not well understood, and the aforementioned project seeks to address this research need through analysis and testing of piles in both virgin and improved soils.

Due to the nondestructive nature of the small-scale wave propagation tests described herein, the payload project was executed with minimal disturbance to the NEESR-SG project. However, as an added precaution against the high-frequency pile vibrations elevating the

pore pressures in the surrounding soil which could alter the pile-soil contact conditions, the payload tests were performed on reaction H-piles instead of the pipe test piles of the NEESR-SG project. The two reaction piles tested in unimproved and improved soil profiles will be referred to as piles U and I, respectively.

2. Background: Dynamic foundation testing has traditionally involved the use of single mode tests, with vertical and horizontal loading cases examined separately [4], often with sinusoidal tests performed sequentially at discrete excitation frequencies (i.e. stepped-sine testing). However, dynamic loads in nature such as those caused by earthquakes, wind, waves, explosions or traffic are inherently multi-directional and contain a wide range of frequency components simultaneously. As has been shown in recent studies of the dynamics of surface as well as deep foundations [5-11], the halfspace models commonly used to calculate frequency dependent impedance functions (stiffness and damping) of the soil or soil-foundation system can usually be fit to only a single mode of vibration at a time, with significant error resulting for the other modes. While others have suggested the use of different half-space models for different vibration modes, such a philosophy is not sufficiently general for arbitrary loading conditions, and misses the opportunity to advance our understanding of the mechanics of soil-structure interaction at a fundamental level.

To address the problem, experimental capabilities were developed in this investigation to provide realistic multi-modal dynamic excitation of pile foundations over a wide range of frequencies. In particular, techniques developed through centrifuge testing of both shallow and deep foundations [5-10] were extended for the first time to full-scale pile foundations. These techniques include the use of the hybrid-mode vertical eccentric (VE) test, in which simultaneous vertical and coupled lateral-rocking motions of the foundation are stimulated using a vertical excitation that is offset horizontally from the centroid of the pile cap. The result is a combination of a vertical force and net moment at the foundation centroid, activating the vertical and coupled lateral-rocking modes of vibration simultaneously. To examine the equivalence of a single VE test to the traditionally separate combination of tests having vertical and horizontal forcing, two other test types were performed in this study. These are the vertical centric (VC) test, in which a vertical load is applied above the foundation centroid, and the horizontal centric (HC) test, in which a horizontal force is applied at an arbitrary elevation in the vertical plane of the centroid. For a symmetric pile cap, the VC test will invoke a purely vertical response, while the HC test will invoke a planar

response consisting of coupled horizontal and rocking modes. Increased testing efficiency will be gained by demonstrating the equivalence of a single VE test to the combination of traditionally separate VC and HC tests. Furthermore, the VE test minimizes stress history effects that arise when VC and HC tests are performed sequentially on the same pile, and alleviates concerns over the equivalence of soil properties when VC and HC tests are performed on separate piles and their response combined to obtain the general behavior for multi-directional excitations. In addition to the benefits outlined above, the present payload project provides a valuable opportunity for the first full-scale verification of numerous experimental findings from centrifuge studies of pile vibration tests performed at the University of Colorado at Boulder [5,7,10], and further refinement of advanced computational continuum boundary element models developed to simulate the observed dynamic behavior of the soil-pile system [10]. Additionally, the first full-scale calibrations will be obtained for simplified engineering procedures [7] for rectifying the poor performance of basic continuum theories for pile-soil interaction.

3. Soil and Pile Properties: Testing was performed next to the Neosho River in Miami, Oklahoma on September 27th through 29th, 2010. The test site consists of a 3.6 ft thick layer of lean clay with gravel and occasional construction debris followed by 9.2 ft of silty clay to clayey silt underlain by 8.2 ft of sandy gravel and limestone bedrock at a depth of 21 ft. Site investigation and in-situ testing performed for the NEESR-SG project includes SPT tests, CPT and DMT soundings, and piston samples. Laboratory tests were also carried out for grain-size analysis, Atterberg limits and unconfined compressive strength.

Both of the HP 10x42 piles tested in this study have a total length of approximately 25 feet and were installed by a vibratory hammer to embedment depths of 245 inches for pile I and 242 inches for pile U. The above-ground unembedded lengths are 55.75 inches for pile I and 57.75 inches for pile U. The cylindrical CDSM improved zone around pile I has a diameter of 48 inches and a depth of 13 ft. The estimated capacity of the pile in unimproved soil is 168 kips in compression and 35 kips in tension, which increases to 374 kips in tension and 240 kips in compression for the pile in improved soil.

It is anticipated that the results and interpretation of in-situ and laboratory testing will be discussed in detail in future publications related to the NEESR-SG project.

4. Design of Excitation, Instrumentation and Data Acquisition Systems: To test the piles under dynamic

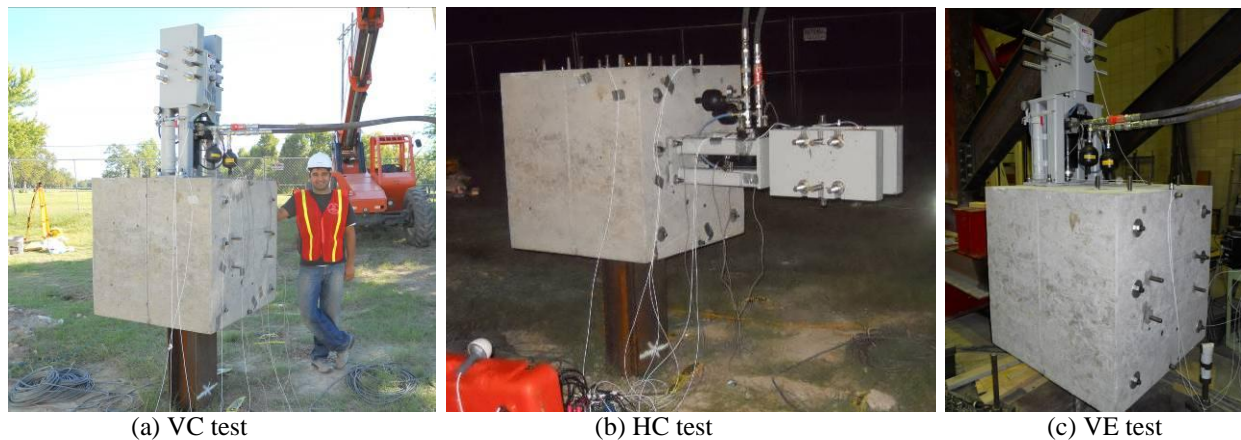


Figure 1: Inertial shaker configurations for the three test types

loading, a two-piece modular pile cap was constructed. The pile cap is 3x3x3 ft in size and has a recess on each half forming a cavity such that the two pieces fit around the H-pile and are bolted together with six $\frac{3}{4}$ inch threaded rods. The cavity extends to 8 inches below the top of the pile cap, so that the H-pile is embedded 28 inches into the cap. To ensure that tight contact would be achieved with various piles having slightly different tolerances, four steel shims were fabricated for insertion between the flanges of the H-pile and the inside of the pile cap. To ensure rigid body motion of the pile cap, a dense frame of reinforcing steel was designed using #5 bars, with #3 bars used for J-hooks.

As mentioned above, this study is focused on random vibration techniques applied to dynamic pile-soil interaction problems. Such techniques typically involve the excitation of a physical or electrical system over a wide range of frequencies, and complementary measurement techniques which efficiently characterize the system response in terms of Fast-Fourier Transforms (FFTs), correlation functions, spectral densities, transfer functions, coherence functions, and impulse response functions. Compatible excitation types are those that can deliver energy over the measurement bandwidth of interest; typically random (white noise or pink noise), impulse or swept-sine signals. One of the experimental goals of this study is to evaluate the relative effectiveness of these three excitation types over a range of amplitudes. Although a linear hydraulic actuator could be used to deliver the forcing, such an excitation source would require construction of a massive, costly and time-consuming reaction frame each time a test was performed. Additionally, linking the test structure to a reaction frame by an actuator can cause kinematic constraints leading to unwanted transverse forces applied to the structure. In this study, an efficient, portable testing system was desired which could be used at a variety of sites in the future without the need for reaction frames or a large generator to run an electric

hydraulic pump. To meet these criteria, a servo-hydraulic inertial shaker system was designed and built by Anco Engineers to the specifications of the PI. The key requirements were the capability to deliver user-specified broadband dynamic forcing with up to 2,000 lb of force over a bandwidth of 1-200 Hz, selectable force or displacement feedback control, and a modular design such that inertial reaction masses could be added by hand without the need for a crane. The shaker has a weight of 300 lb, of which 115 lb is a moving carriage. For variable control over the shaker's spectral performance curve, up to 14 extra masses weighing 48 lb each can be mounted on the carriage in pairs, giving a maximum moving mass of 787 lb. Adding extra masses provides greater force at low frequencies but decreases the maximum usable frequency. Because the schedule in this study was limited to a few days for payload tests, it was not possible to perform a parametric study to determine the optimum number of reaction masses for the given pile-cap-soil configuration. However, it was determined that four pairs of extra masses comprising a total reaction mass of 499 lb provided a good balance between low and high-frequency performance. The shaker is shown with 8 reaction masses in Figure 1a and b, and without reaction masses in Figure 1c. Its control system features a proportional integral (PI) feedback control loop with a user-generated command signal and requires a hydraulic power supply with 3,000 psi pressure at a flowrate of 10 gallons per minute (GPM). To provide this capability in a portable package without the need for a large pump or generators, a Riemann & Georger Corporation model HV2310 Hydrapak gas-powered hydraulic pump with a 6-gallon tank was used. The Hydrapak was modified to use 5 micron filtration as required for use with the shaker's servo-valve, and the pressure was adjusted down from the stock 3400 psi to the required 3000 psi. During preliminary testing, it was found that the hydraulic oil was overheating due to the closed-center configuration of the servovalve, whereas the Hydrapak is typically used with open-

center servos. If allowed to overheat, the oil would damage the servovalve, requiring a costly repair. To eliminate overheating, the cooling capacity of the system was tripled by inserting a large auxiliary heat exchanger (Hayden Industrial model TTEC 20924) in the loop between the existing heat exchanger and the oil reservoir.

For data acquisition and real-time analysis in the time and frequency domains, a dynamic signal analyzer was programmed in LabVIEW. The analyzer features recording and display of time-histories, FFTs, spectral densities, transfer functions and coherence functions, and allows for a variety of excitation types including random, swept-sine and user-defined signals, with standard windowing and averaging capabilities built in. The hardware components of the network analyzer consist of a National Instruments (NI) cDAQ 9172 USB chassis, five NI model 9234 4-channel analog input modules with 24-bit resolution and 51.2 kHz maximum sampling rate, and a NI 9263 analog output module for generating the command signal for the shaker. When performing frequency domain measurements, the sampling rate is either chosen directly or is typically calculated based on the requested measurement bandwidth and number of data points or frequency lines. The LabVIEW analyzer program follows the standard practice of setting the sampling rate to 2.56 times the requested measurement bandwidth. Choosing the number of data points to acquire then fixes the frequency resolution Δf . Additionally, most analyzers typically store only the final of a number of time-histories when performing spectral averaging, and this convention was followed in the LabVIEW program to maintain throughput performance. Since the act of sampling the data at a given rate and saving only the last of a number of time-histories both represent some loss of information, complete time-histories of the test data were also recorded for all signals so that users of NEEShub could evaluate the data using their own chosen techniques and sampling parameters. The complete time histories also allow the frequency domain measurements to be reconstructed in the event of lost data. All data signals were therefore split and the complete time-histories were recorded on the nees@UCLA Kinemetrics Granite seismic monitoring systems (Figure 2) at the maximum possible sampling rate of 1000 Hz.

5. Measurement Approach: In all tests, accelerations of the shaker and pile cap were recorded in the x (horizontal) and z (vertical) directions in the plane of motion of the pile cap using PCB Model 353B33 accelerometers, labeled as shown in Figure 3. The acceleration of the shaker's moving mass in the

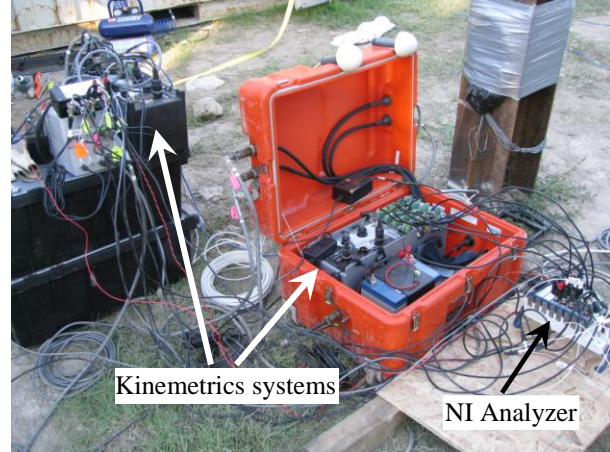


Figure 2: National Instruments dynamic signal analyzer and Kinemetrics Granite data acquisition systems

direction of shaking is denoted A_{mm} and is proportional to the dynamic force delivered to the pile cap. For use with careful analytical evaluation of higher-order loading effects, the acceleration of the shaker's moving mass transverse to the excitation direction was also measured, denoted A_{mt} . Vertical acceleration of the pile cap was measured at the two edges, denoted A_{z1}^c and A_{z2}^c , the average of which gives the acceleration of the top-center point of the pile cap. Similarly, horizontal accelerations were measured, denoted A_{x1}^c and A_{x2}^c , respectively in Figure 3. Accelerations were also recorded in the soil using 7 nees@UCLA Episensor triaxial accelerometers buried 6 inches below the soil surface as shown in Figure 4. Additional NEES resources from UCLA used in this study include the Mobile Command Center (MCC), telepresence cameras and the wireless network.

During testing, the acceleration signals were recorded by the NI analyzer in the time-domain and processed in the form of power spectral densities (PSD), coherence functions (COH) and transfer functions (XFER). The transfer function between a system input $x(t)$ and output $y(t)$ can be defined as

$$H_{xy}(f) = \frac{\bar{G}_{xy}(f)}{\bar{G}_{xx}(f)}, \quad (1)$$

in which f is frequency and $\bar{G}_{xy}(f)$ denotes the cross-spectral density of input and output and $\bar{G}_{xx}(f)$ is the auto-spectral density of the input (see [12]). In Equation (1), bars over the spectral densities denote ensemble averages, which are performed to minimize measurement errors due to random sources of noise. The coherence function,

$$\gamma_{xy}^2(f) = \frac{|\bar{G}_{xy}(f)|^2}{\bar{G}_{xx}(f)\bar{G}_{yy}(f)} \quad (2)$$

is an indicator of measurement quality that takes a value of unity for a perfectly linear, time invariant system with no added noise. Deviations from any of these conditions cause the coherence to decrease towards zero.

To ascertain the level of ambient vibration caused by background sources such as generators and engines, nearby traffic and trains and micro-seismic activity, accelerations were recorded before and after starting the portable hydraulic power supply, without excitation from the shaker. Such ambient tests are useful for an understanding of the signal to noise ratio in subsequent forced vibration tests. If the ambient sources are of sufficient magnitude, they can also be useful for characterizing the properties of the dynamic system, examples of which include centrifuge testing [12] or Refraction Micro-tremor studies. Following the ambient tests, three different types of forcing signals were used to excite the pile, referred to as random (R), chaotic impulse (C) and swept sine (S).

Theoretically, the broadband random signal (R) contains energy at all frequencies in the selected bandwidth uniformly, i.e. the spectral density is constant. Due to physical limitations of the system, however, the spectral density of the delivered forcing is not uniform, but is of sufficient amplitude across the frequency band of interest to excite the response of the soil-structure system above the ambient levels.

The chaotic impulse signal (C) can be defined as a series of randomly timed impulses with randomly distributed amplitudes. This type of excitation was found to be useful in centrifuge and field-scale studies of pile and footing vibration. For testing configurations in which an electromagnetic exciter is used to deliver random forcing to a footing or pile through a load cell mounted on the structure, chaotic impulses can be generated by sending the exciter a random signal while moving its center of motion away from the load cell. The nature of the random excitation signal then creates a succession of randomly timed impulses in between which the structure undergoes free-vibration. To avoid excessive periods of free vibration which would lead to decreased coherence between the force and response, the durations between impacts are then adjusted by altering the exciter's center of motion to maximize the observed coherence. In aforementioned test setups using a load cell, the chaotic impulse technique has the effect of improving coherence and therefore quality of transfer functions by minimizing unwanted frictional

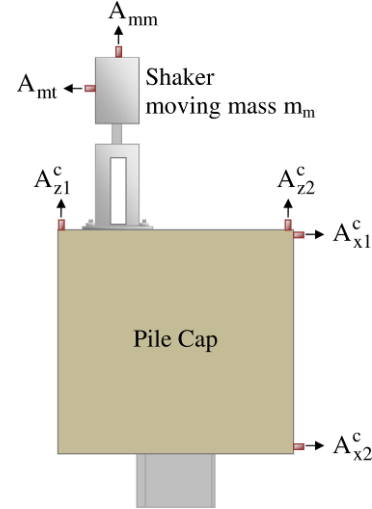


Figure 3: Orientation and notation for accelerometers on shaker and pile cap (shaker in VE test position)

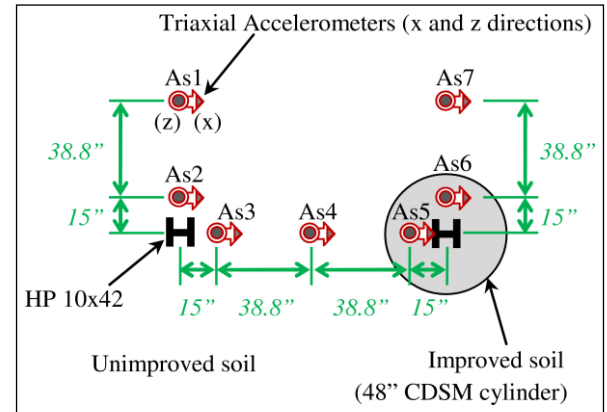


Figure 4: Plan view showing layout of the two test piles and soil accelerometers

effects. Because of its demonstrated usefulness in creating alternating forced and free vibration periods for effective stimuli in dynamic foundation testing, the chaotic impulse excitation technique was examined in this study to evaluate its effectiveness when used with an inertial shaker system. Contrary to the electromagnetic exciter configurations in which the exciter was not rigidly attached to the test structure, it is not possible to create impacts with the inertial shaker because it is attached to the pile cap. Chaotic impulse excitation was thus simulated in this study by sending the shaker a control signal consisting of the force time-history recorded by a load cell in a previous good quality chaotic impulse test of a surface foundation (see [13]). During testing, it became evident that the time scale of the user-defined input signal became compressed, resulting in impulses occurring more rapidly than actually occurred in the footing test in which the force signal was measured. Although the larger mass and lower fundamental period of the pile

cap relative to the footing should logically be accounted for by a scaling of the time axis, the scaling applied by the LabVIEW program was counter to the desired result. Due to the short time allotted for payload testing, there was insufficient time to correct the issue in the field, so chaotic impulse tests were performed using the time-compressed signal. The issue is currently being addressed, and additional tests will be planned for further evaluation of the technique.

The third type of excitation used is swept-sine (S), in which the frequency of a sinusoidal signal is continuously swept over the measurement bandwidth at a chosen rate. While random excitation signals partition the energy across the frequency spectrum, swept-sine signals concentrate the signal's energy at a single frequency at any given time. Consequently, for the voltage output capabilities of a given measurement system, swept sine signals can be used to deliver larger excitation levels than those obtainable with random excitation, as will be demonstrated in the experimental results that follow.

Because the excitation types described above can deliver energy across the frequency spectrum at once, they are useful for rapid measurement of the system's response in terms of spectral densities or transfer functions. In contrast to traditional stepped-sine tests in which the response is measured for a single excitation frequency at a time (e.g., in eccentric mass shaker setups), random vibration techniques enable measurement of the system response at thousands of frequency points in a matter of seconds, providing much greater efficiency.

The testing program in this study consisted of 1000 Hz bandwidth VC tests on the improved pile (I) using random (R), chaotic impulse (C) and swept-sine (S) excitation performed initially at a low forcing levels (denoted as excitation level 1). In the order performed, these tests were named I-VC-R1, I-VC-C1 and I-VC-S1. The loading intensity was then increased to an intermediate value (level 2), and the tests were repeated, named I-VC-R2, I-VC-C2 and I-VC-S2. Loading intensity was increased to level 3, and tests I-VC-R3 I-VC-C3 and I-VC-S3 were performed, followed by additional unscheduled tests in which the forcing intensity was increased and other experimental parameters were varied. For example, the bandwidth was decreased to 250 Hz to examine the low-frequency behavior in more detail, the loading intensity was further increased, and the sweep speeds of 1, 2 and 3 seconds were used. Upon conclusion of the VC tests, the shaker was moved to the HC position and the suite of tests repeated (i.e. tests I-HC-R1, I-HC-C1, etc.), followed by hybrid-mode VE tests (I-VE-R1, I-VE-C1,

etc.). The pile cap was then removed from pile I and mounted on pile U and the program of tests was repeated, with the prefix I changed to U in the test names.

For the real-time frequency domain processing observed during the experiments, the acceleration of the shaker's moving mass was treated as the stimulus signal and all other accelerations of the pile cap and soil were treated as response quantities. In addition to the spectral measurements stored by the NI signal analyzer, the complete time-histories of all signals were recorded by the nees@UCLA Granite data acquisition systems, which will enable additional analyses to be performed by the NEES community using their chosen techniques and bandwidths. For example, using the raw data, one could compute transfer functions between the pile-cap and soil, or between different points in the soil for calibration of theoretical and computational models of the dynamic pile-soil interaction. In all, a total of 109 tests were performed producing approximately 12 GB of data, which is currently being organized and prepared for upload to the NEEShub.

6. Preliminary Test Results and Interpretation: The tests were performed weeks prior to the submission of this paper, and the results and interpretation presented herein should therefore be considered as preliminary. Typical time-histories of the vertical acceleration at the top-center position, the upper horizontal accelerometer, and vertical acceleration of the shaker's moving mass are shown in Figure 5a, b and c, respectively, for test I-VE-R3, i.e. random excitation of the pile in improved soil (see above for a description of the test naming convention). Similar time-histories are shown in Figure 6 for chaotic impulse and Figure 7 for swept sine excitation. The corresponding power spectral densities are shown in Figure 8 through Figure 10, from which it can be seen that random and swept-sine excitations generally provide the most uniform power spectral densities, while chaotic impulse delivers the least uniform PSD. As can be seen in the time histories, the VE test successfully generated significant horizontal rocking motion as evidenced by the horizontal accelerations, which are slightly larger than the vertical ones. The relative amplitudes of the vertical and horizontal responses can be adjusted in VE tests by prescribing a different eccentricity of the vertical load.

As mentioned above, it was discovered during testing that the chaotic impulse excitation signal extracted from a load cell measurement in a surface footing test was scaled slightly incorrectly in the LabVIEW program, with the timing of the impulses being more regularly spaced than desired. As can be seen in Figure 6, this resulted in impulses being applied at a rate of roughly

11 Hz with secondary impulses in between. The power spectral density of this signal (Figure 9) therefore appears similar to what would be seen for an 11 Hz periodic impulse, with higher harmonics spread out at 11 Hz intervals. The implementation of the chaotic impulse technique is currently being refined in LabVIEW, with the expected result that the frequency spectrum will become smoother and resemble that of random loading once the nearly periodic impulses are corrected to have a more random temporal distribution.

Acceleration transfer functions and related coherence functions corresponding to the vertical accelerations shown in parts a and c of the above figures can be seen in Figure 11 through Figure 13. Also plotted in these figures are results from the two smaller forcing levels. The VC/VE transfer functions are ratios of VC acceleration of the center of the pile cap to the VE acceleration of the shaker moving mass. The transfer functions shown exhibit the expected trend of a single gentle peak followed by a horizontal asymptote, which can be seen by plotting the results in terms of their complex magnitude as will be shown later. As demonstrated in these figures, good coherence was obtained over a wide frequency range, and a small extra bump can be seen prior to the major vertical resonance peak. This phenomenon is related to the lack of perfect symmetry of the pile cap, and a similar behavior was observed in the centrifuge pile vibration tests reported in [5]. In the centrifuge study, the extra hump in the vertical response was shown to arise from the horizontal offset of the centroid of the composite cap-instrumentation system, and was a useful tool to demonstrate the accuracy of the analytical treatment. As can be seen in the transfer functions of Figure 11 through Figure 13, the three different levels of load resulted in slight nonlinear effects for the cases of random and swept sine excitation, as evidenced by small changes in the shapes and frequencies of the peaks. The chaotic impulse excitation, however, resulted in nearly identical VC/VE transfer functions for all three load levels studied, owing to the relatively small differences in the three power spectral densities shown in Figure 9.

The transfer functions are complex valued, and can thus be presented either in terms of real and imaginary components, or magnitude and phase. For brevity, only the magnitudes will be shown from this point on to allow for a more efficient comparison between different test configurations. While a complete examination and comparison of all test results is beyond the scope of this paper, and numerical simulation of the dynamic tests is forthcoming, a few interesting conclusions can be drawn by comparing responses from the different test types and soil types. For example, Figure 14 contains a

comparison of the vertical and horizontal responses obtained from separate VC and HC tests, as compared to those from a single VE test. As shown in the figure, the VE test is successful in capturing the vertical mode of vibration, with a small extra bump that can be explained by the slight differences in the inertial symmetry of the pile cap owing to the offset shaker position in the VE tests. While the HC test is seen to produce a stronger fundamental peak around 8 Hz, the VE test is also effective at uncovering this resonant frequency. It should be noted that theoretically, the magnitudes of the HC/VE and HC/HC responses are not equal, owing to the different location and direction of the excitation force in these two tests. The resonant frequencies, however, should coincide. As mentioned previously, higher forcing levels were examined in addition to different sweep rates in the swept sine tests, and it was determined that adjusting these parameters could enable one to capture a sharper fundamental peak in the VE test. The VE tests thus represents an efficient technique for capturing simultaneously the vertical and coupled lateral-rocking response of pile-soil systems, while alleviating concerns regarding different soil and contact conditions in separate VC and HC tests.

Finally, the effect of the improved soil on the dynamic response of the pile can be seen in Figure 15. As perhaps can be expected, the improved soil results in a stiffer response in the vertical mode, as evidenced by an increase in the VC/VE resonant frequency. Contrary to expectations, however, the fundamental lateral rocking peak frequency around 8 Hz in both HC and VE tests seems to be unaffected by the presence of the stiff CDSM zone, while the second peak exhibits a slight change. This behavior may be related to smaller initial pile-soil contact stresses resulting from inserting the pile into the CDSM mixture before it sets, as opposed to higher lateral stresses caused by forcing the pile into the unimproved but also undisturbed soil. This interesting and unexpected result warrants further study.

7. Conclusions: preliminary results of a study of full-scale dynamic soil-pile interaction via random vibration techniques were presented in this paper. Development of the experimental equipment and data acquisition systems and software was described, and solutions were detailed for a number of challenges encountered in the study. Examples of the measured dynamic responses in the form of time-histories, spectral densities, coherence functions and transfer functions were demonstrated, and the validity of the hybrid mode VE testing technique was verified for the first time for full-scale pile foundations. Additionally, the performance of the portable and efficient servo-hydraulic inertial shaker system as an alternative to more costly hydraulic actuator and reaction frame configurations was

demonstrated. For true understanding and advancement of the state of the art and state of practice, experimental measurements must be evaluated against current techniques of design and analysis. In the present computational modeling phase of the study, three-dimensional boundary element continuum models of the pile and soil domain are being used to analyze various aspects such as pile installation and the spatial distribution of modulus and damping of the soil. The goal is to create enhanced experimental simulation techniques for characterizing dynamic soil-pile interaction guided by insights from the experimental tests presented herein.

Although the experimental testing was only recently completed, preliminary examination of the results indicates that a number of the project goals have been successfully achieved. It is hoped that the experimental design and techniques described herein will expand existing NEES capabilities and test types, and that the measured data will be of value to the NEES community once archived on the NEEShub.

8. Acknowledgements: The support of the NEES program of NSF through grant award CMMI-0936627 is gratefully acknowledged.

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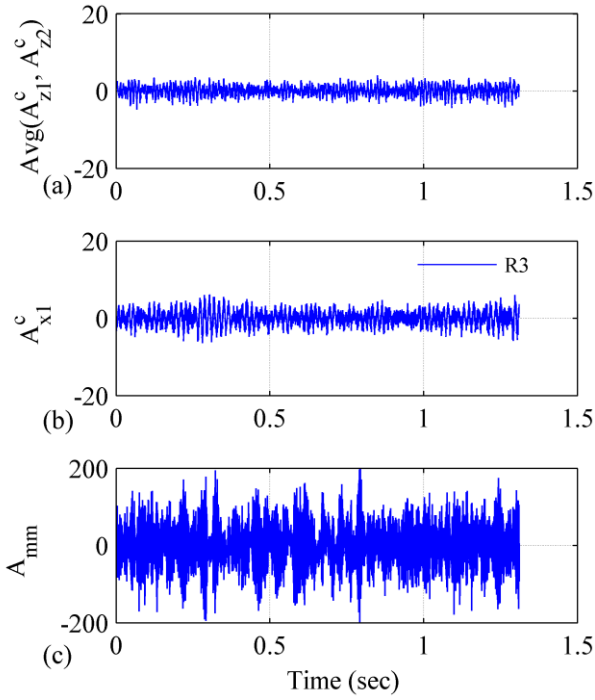


Figure 5: Acceleration time histories (m/s^2) for VE random excitation of pile in improved soil, test I-VE-R3.

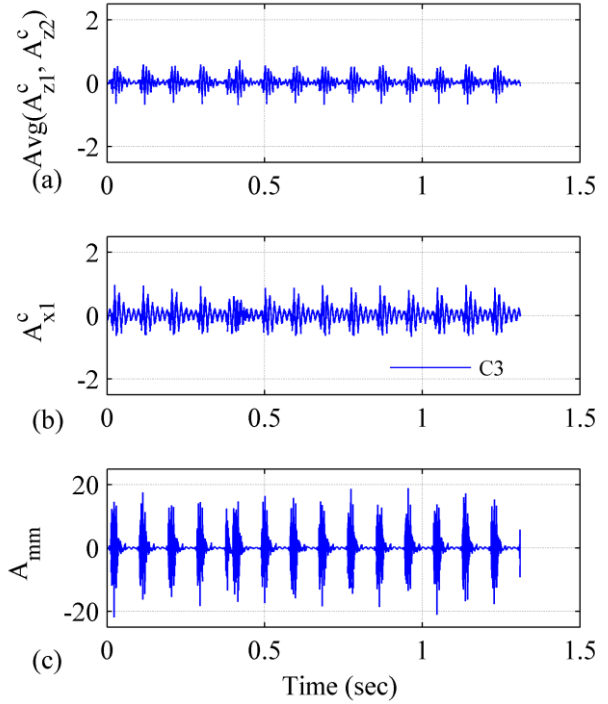


Figure 6: Acceleration time histories (m/s^2) for VE chaotic impulse excitation of pile in improved soil, test I-VE-C3.

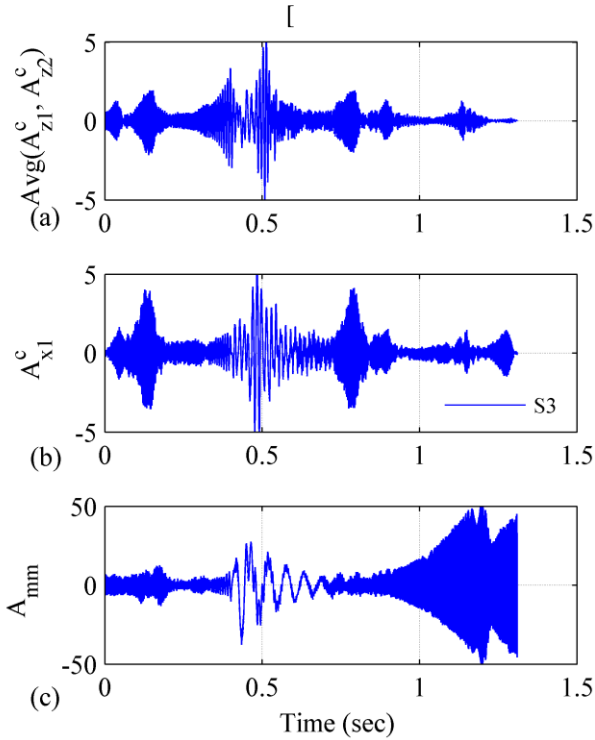


Figure 7 Acceleration time histories (m/s^2) for VE swept-sine excitation of pile in improved soil, test I-VE-S3.

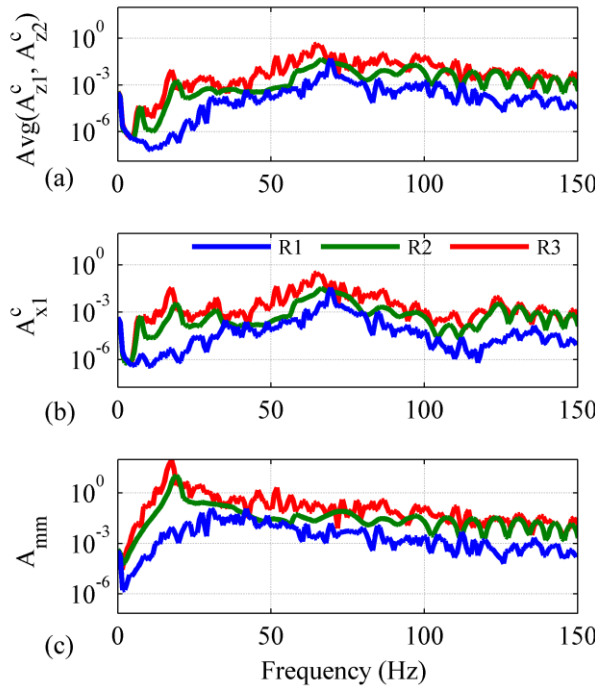


Figure 8: PSD ($(\text{m/s}^2\text{rms})^2/\text{Hz}$) for VE random excitation of pile in improved soil.

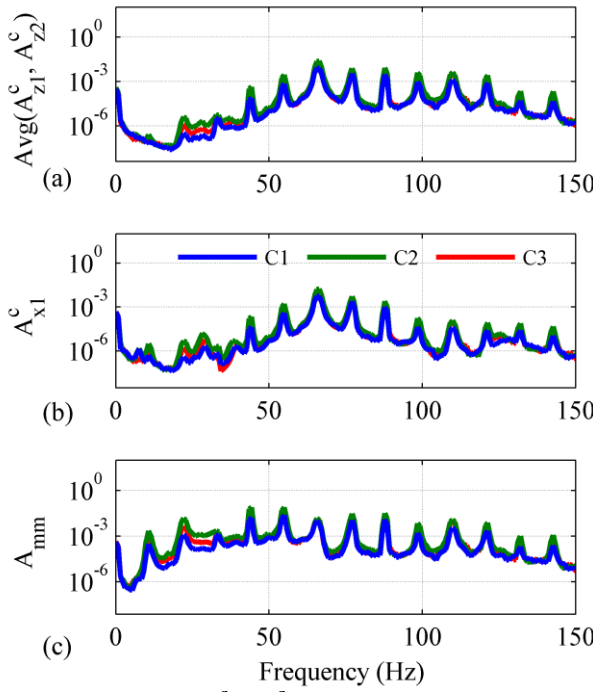


Figure 9: PSD $((\text{m/s}^2\text{rms})^2/\text{Hz})$ for VE chaotic impulse excitation of pile in improved soil.

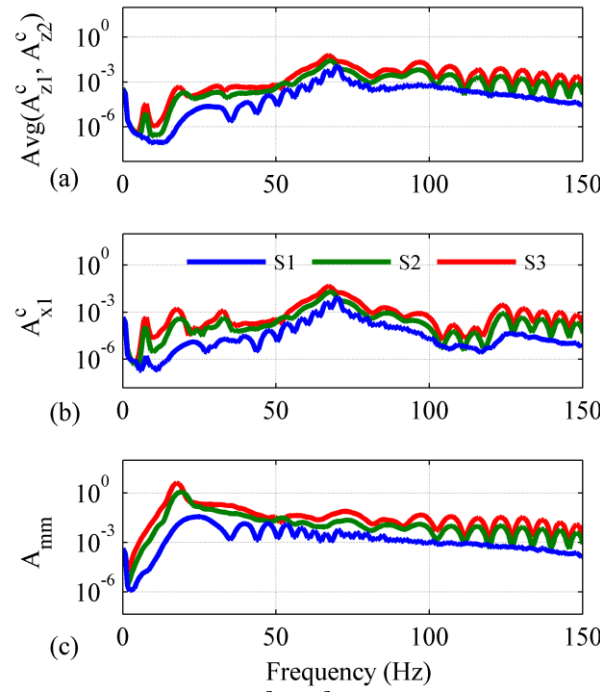


Figure 10: PSD $((\text{m/s}^2\text{rms})^2/\text{Hz})$ for VE swept-sine excitation of pile in improved soil.

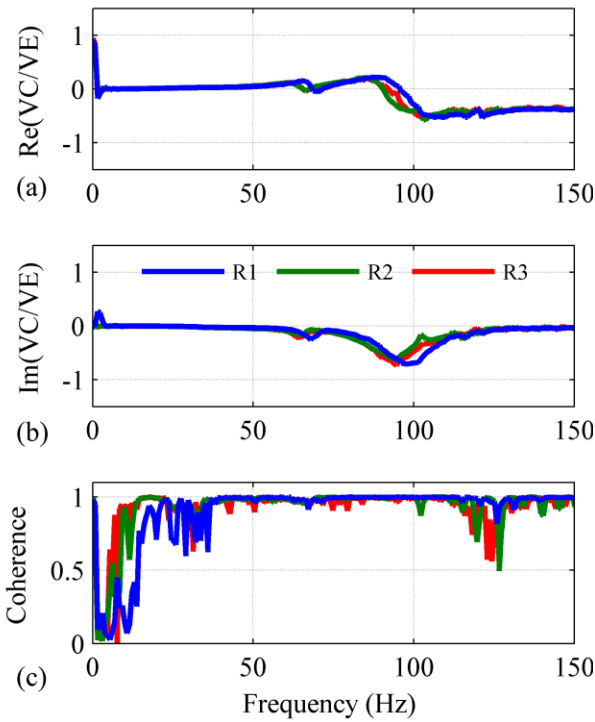


Figure 11: Transfer functions and coherence for VE random excitation of pile in improved soil.

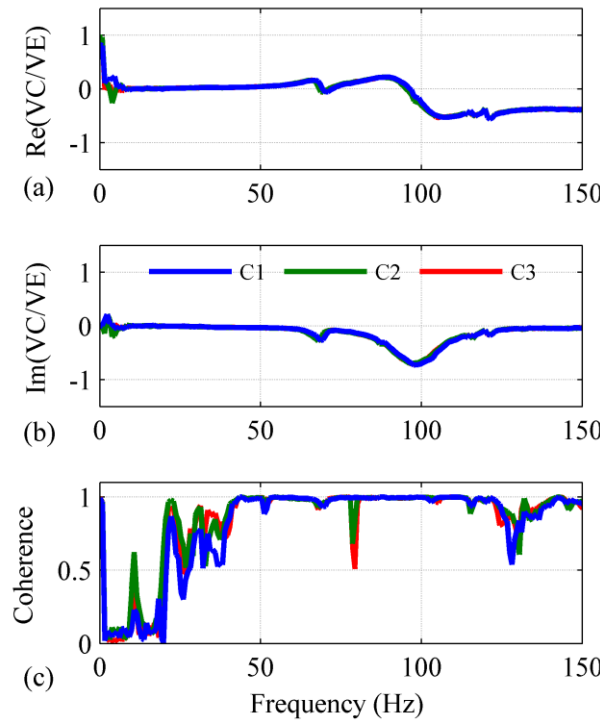


Figure 12: Transfer functions and coherence for VE chaotic impulse excitation of pile in improved soil.

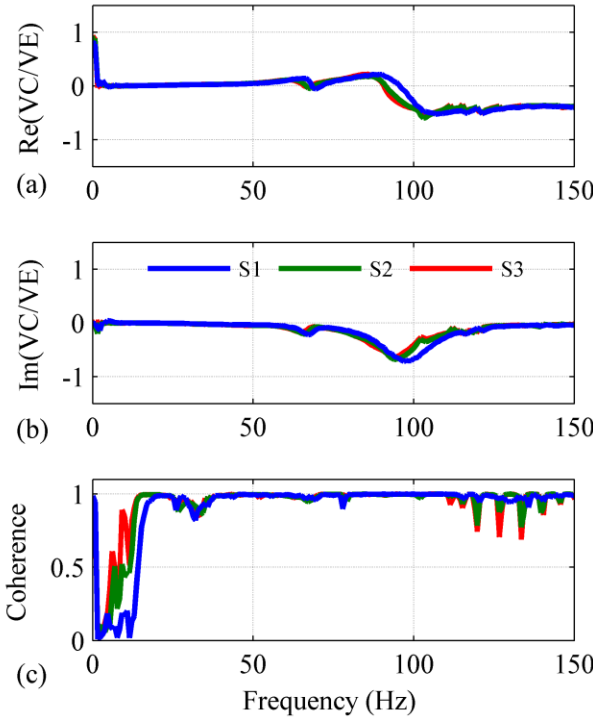


Figure 13: Transfer functions and coherence for VE swept-sine excitation of pile in improved soil.

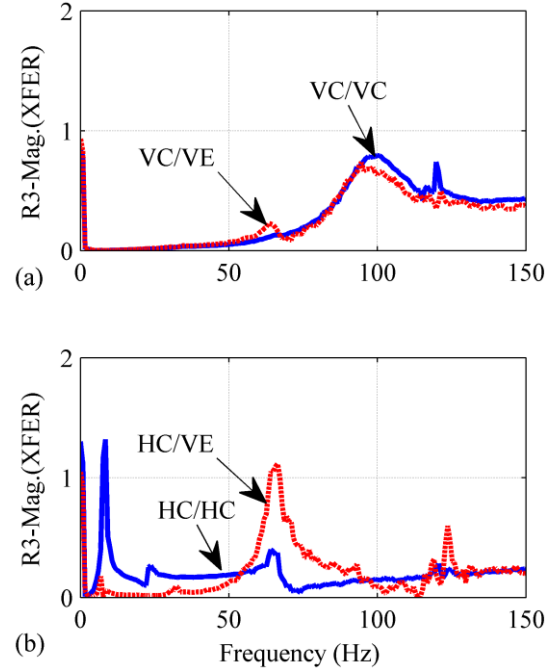


Figure 14: Comparison of VE test to combination of VC and HC tests for random excitation. (a) VC response from VC and VE tests, (b) HC response from HC and VE tests.

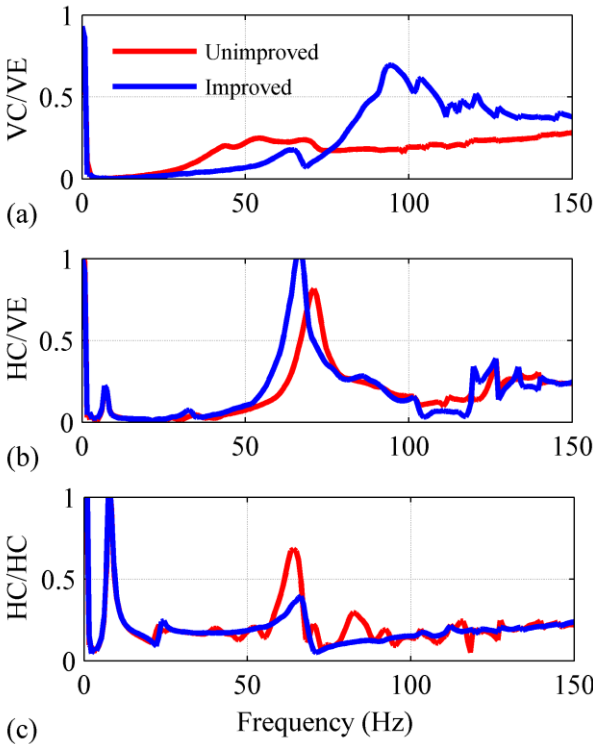


Figure 15: Comparison of VC/VE, HC/VE and HC/HC transfer functions for pile in unimproved vs. improved soil (swept-sine excitation at intensity level 3).